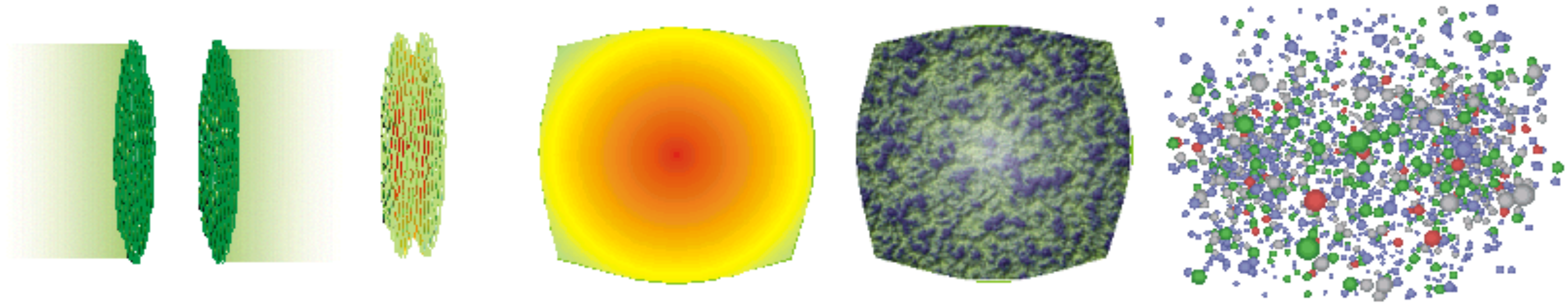
The Color Glass Condensate, the Glasma and Thermalization in Heavy Ion Collisions

(Bose Condensation Too?)



-------------- sQGP ---------------

CGC | Initial Singularity | Glasma | Thermalized sQGP | Hadron Gas

What is the high energy limit of strong interactions?
How do we compute the gluon and quark distributions relevant for asymptotically high energy interactions?
What are the possible states of high energy density matter?
Is there a simple unified description of lepton-hadron and hadron-hadron interactions?

RIKEN BNL Research Center
RIKEN
RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG
HUAZHONG UNIVERSITY
Brookhaven National Laboratory
Office of Science | U.S. Department of Energy
BROOKHAVEN NATIONAL LABORATORY

Color Glass Condensate:

Very high energy density highly coherent gluons that form the high energy hadron wavefunction. This is the matter that forms the Glasma in a collision. It has universal properties. It is made of high intensity transversely polarized gluon fields.

Strongly Interacting Quark Gluon Plasma:

Glasma:

The matter that is formed in the collision of two sheets of Colored Glass, and eventually thermalizes into a thermalized Quark Gluon Plasma. These are initially high intensity longitudinal gluon fields. Later these fields decay into gluons. The gluons are strongly interacting until thermalization. There might also be a gluonic Bose condensate

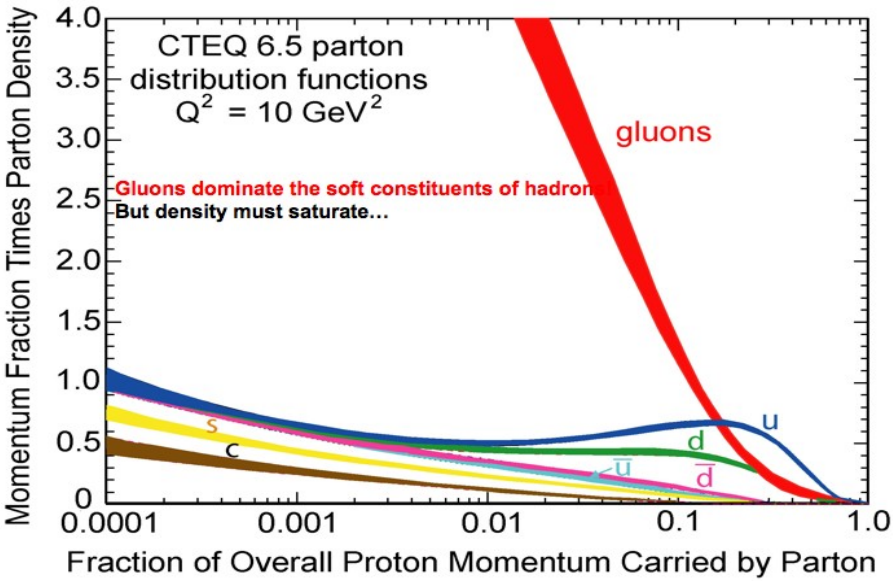
Thermalized QGP:

This occurs after the thermalization of the Glasma, and is the topic of many talks in this meeting. The thermalized Quark Gluon Plasma eventually decays into a hadron gas.

The gluon density is high in the high energy limit:

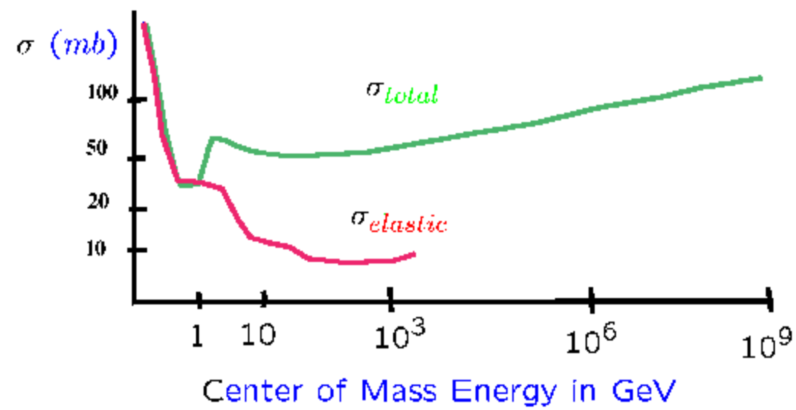
$$x = E_{gluon}/E_{hadron}$$

$$x_{min} \sim \Lambda_{QCD}/E_{hadron}$$

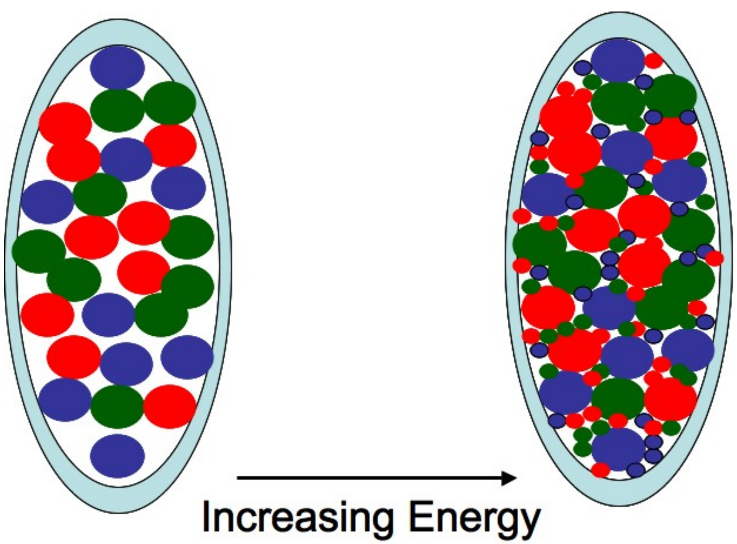


Gluons dominate the proton wavefunction

The total hadronic cross section:



Proton size grows slowly



Asymptotic Freedom: High density systems are weakly coupled because typical distances are short

$$\alpha_S << 1$$

Possible to understand from first principles

Color Glass Condensate

Color:
Gluons are colored

Condensate:
Gluon occupation number $1/\alpha_S$ is as large as can be, like Higgs condensate or superconductor
High density of gluons is self generated

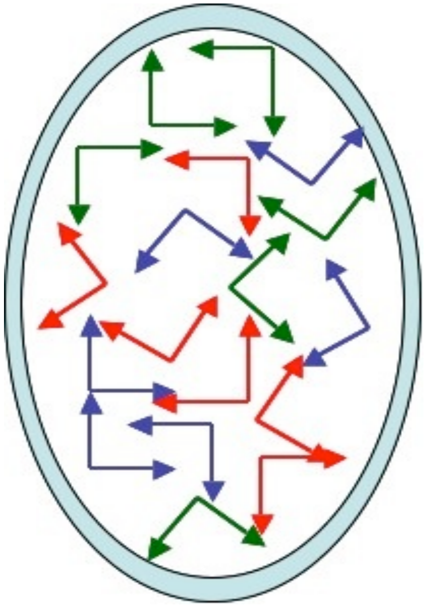
Glass:
The sources of gluon field are static, evolving over much longer time scales than natural one
Resulting theory of classical field and real distribution of stochastic source is similar to spin glass

$$\frac{dN}{dy d^2 r_T d^2 p_T} \sim \frac{1}{\alpha_s}$$

Parton distributions replaced by ensemble of coherent classical fields

Renormalization group equations for sources of these fields

$$Q^2_{sat} >> \Lambda^2_{QCD} \qquad \vec{E} \perp \vec{B} \perp \hat{z}$$



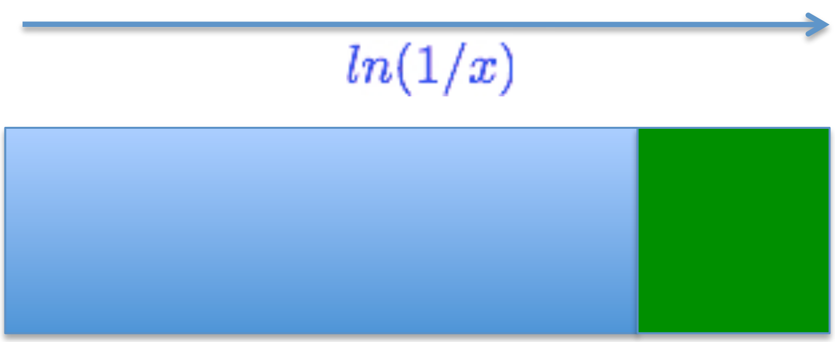
Effective Theory of Color Glass Condensate

$$\frac{dN}{dy\,d^2p_T\,d^2r_T} \sim \frac{1}{\alpha_S} \qquad p_T < Q_{sat}$$

Classical gluon fields at small x
Static sources of gluon fields at large x

Renormalization group changes what is source and what is field as energy increases.
Renormalization group determines distribution of sources

Fixed point of renormalization group => Universality of CGC

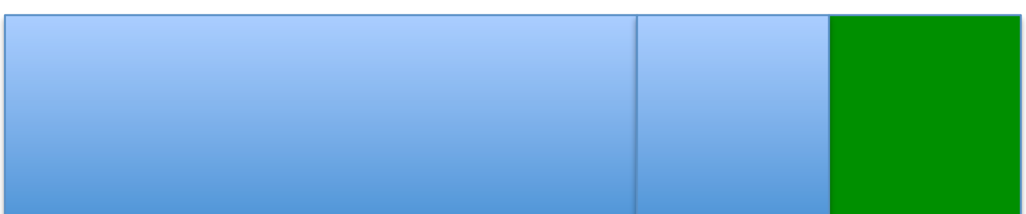


$x \sim 1$ $\qquad x_1 \qquad x_0 \sim Q_{sat}/E_{hadron}$

$$\alpha_s ln(x_1/x_0) << 1$$

Required to treat fields as classical for

$$x_1 > x > x_0$$



$x \sim 1$ $\qquad x_1 \qquad x_2 \qquad x_0' \sim Q_{sat}/E_{hadron}'$

Evolution equations to all orders in the strength of gluon fields: JIMWLK; Balitsky-Kovchegov

Increasing gluon density seen in DGLAP and BFKL evolution equations

Typical gluon size 1/Q

DGLAP:
From momentum Q_0 compute distribution at Q at fixed x
Number of gluons grows but gluons decrease in size rapidly:
Dilute limit

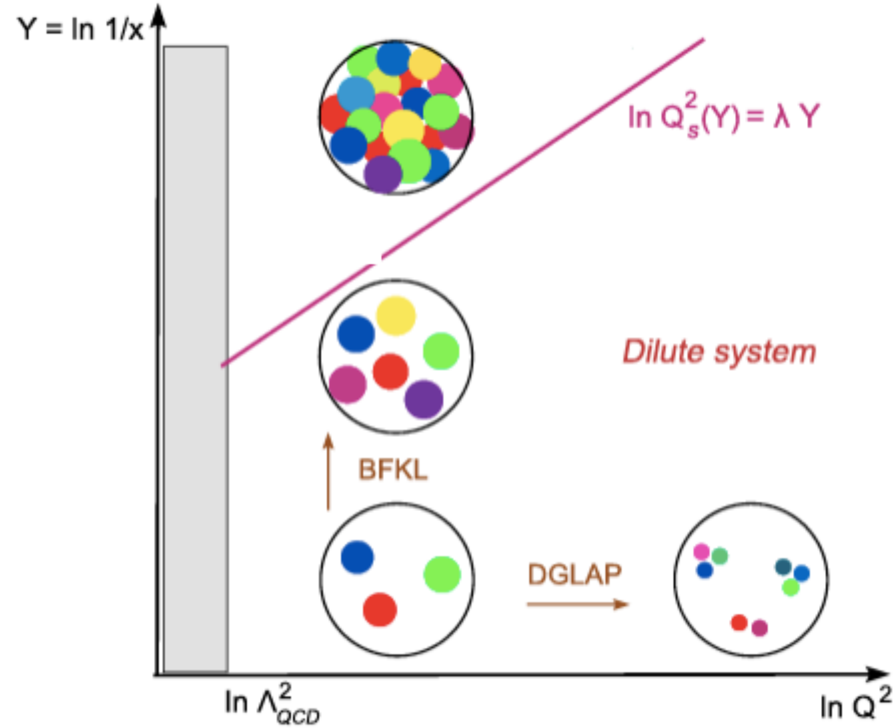
BFKL:
From x_0 to x at Q:
Number of gluons grows but gluons of fixed size:
High density limit

$$q < Q_{sat}$$

Gluons Saturated.

$$Q_{sat}^2 \sim Q_0^2 \left(\frac{x_0}{x}\right)^\delta \qquad \delta \sim 0.2 - 0.3$$

Grows



How does density at fixed size stop growing?

$1/\alpha_s$ gluons with interaction strength α_s are a hard sphere.

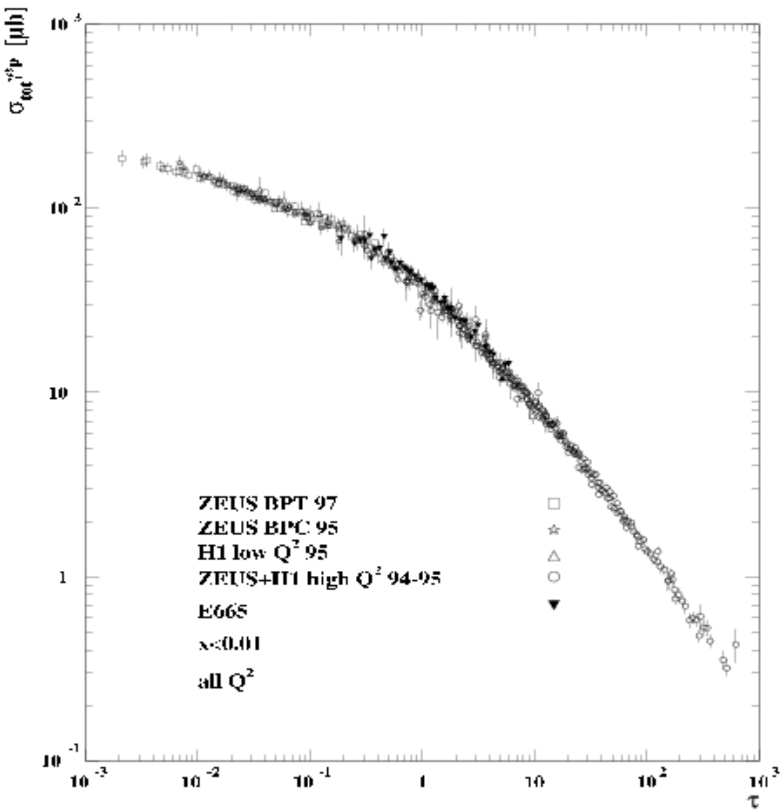
When all gluons with

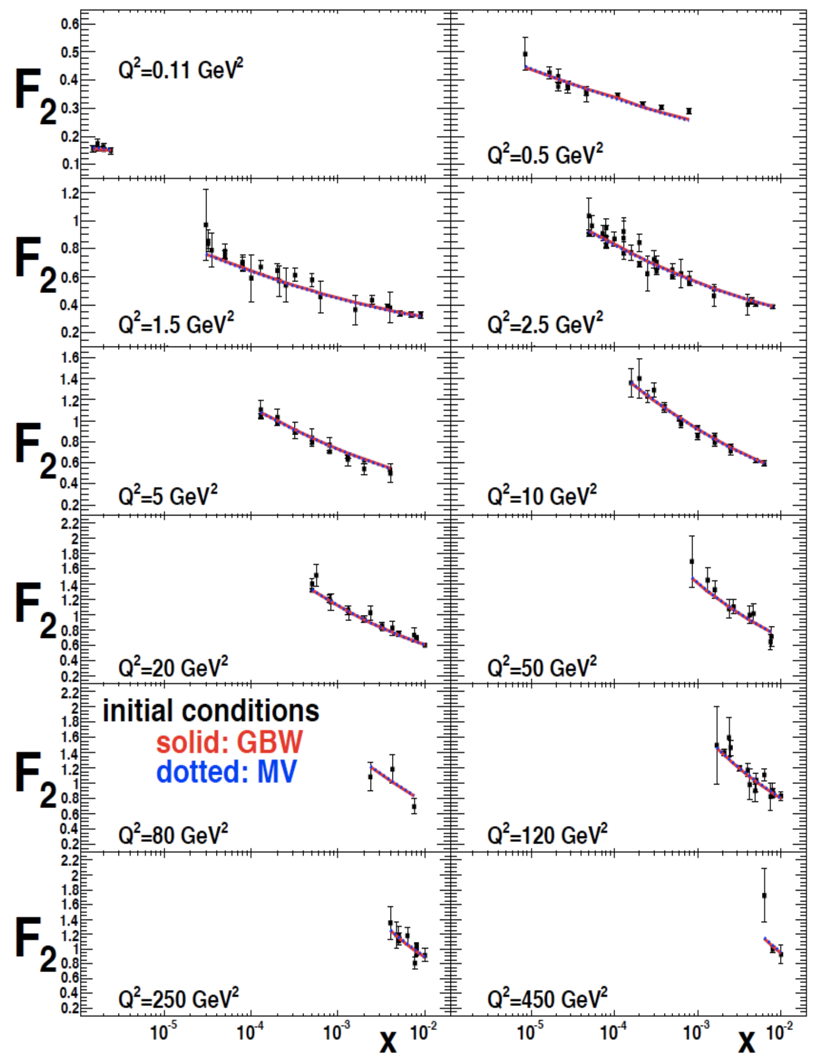
$$q < Q_{sat}$$

are filled, then begin filling with higher momentum

Theory of CGC: First Principles from QCD

Requires saturation momentum $Q_{sat} >> \Lambda_{QCD}$ When is it true?





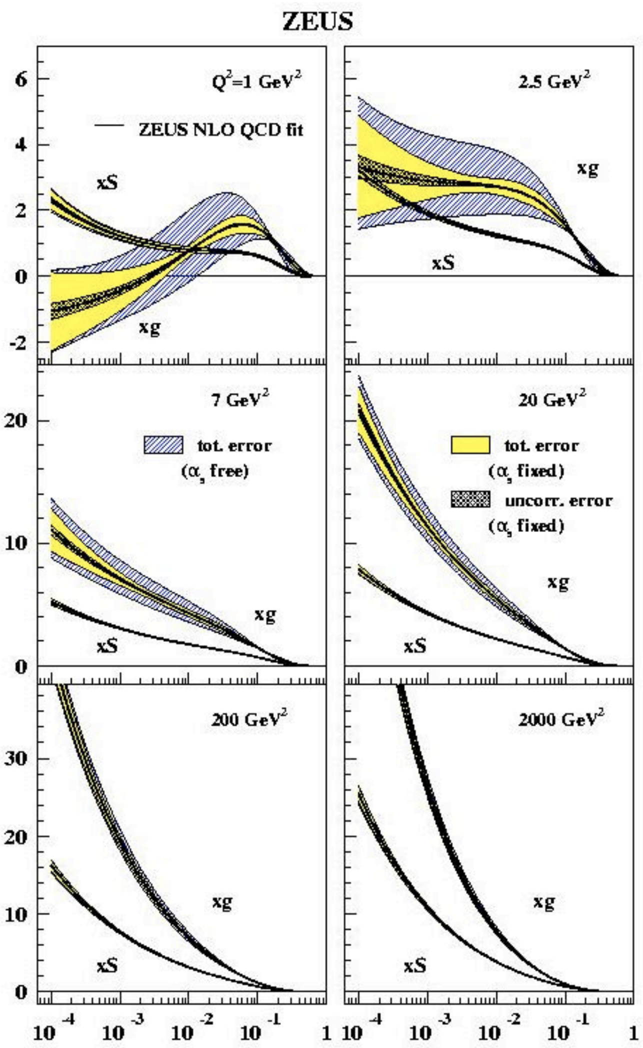
Experimental Evidence: ep Collisions

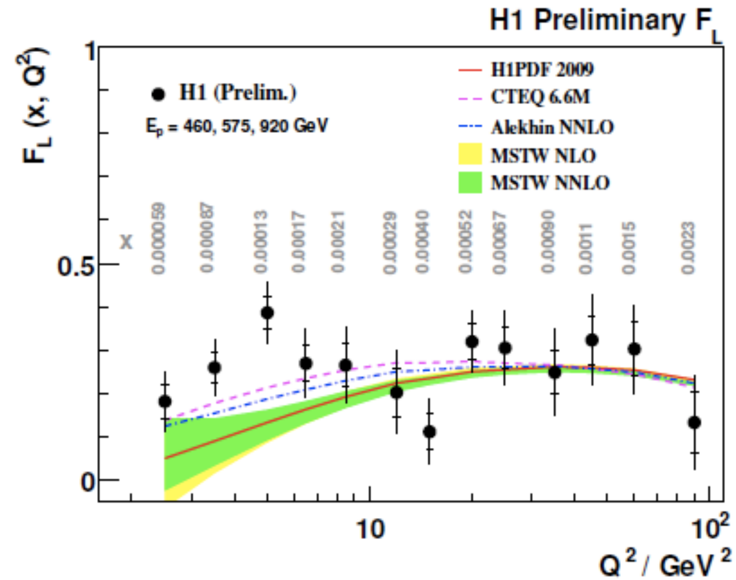
Distributions from NLO BK-JIMWLK evolution

Computed saturation momentum dependence on x agrees with data

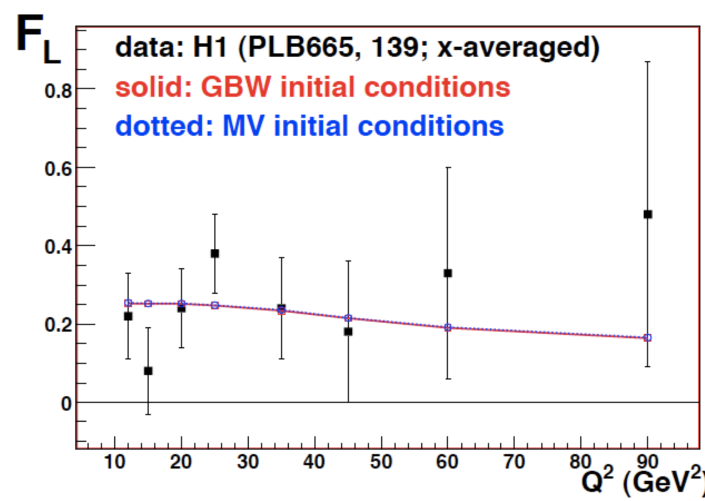
Simple explanation of generic feature of data

Allows an extraction of saturation momentum

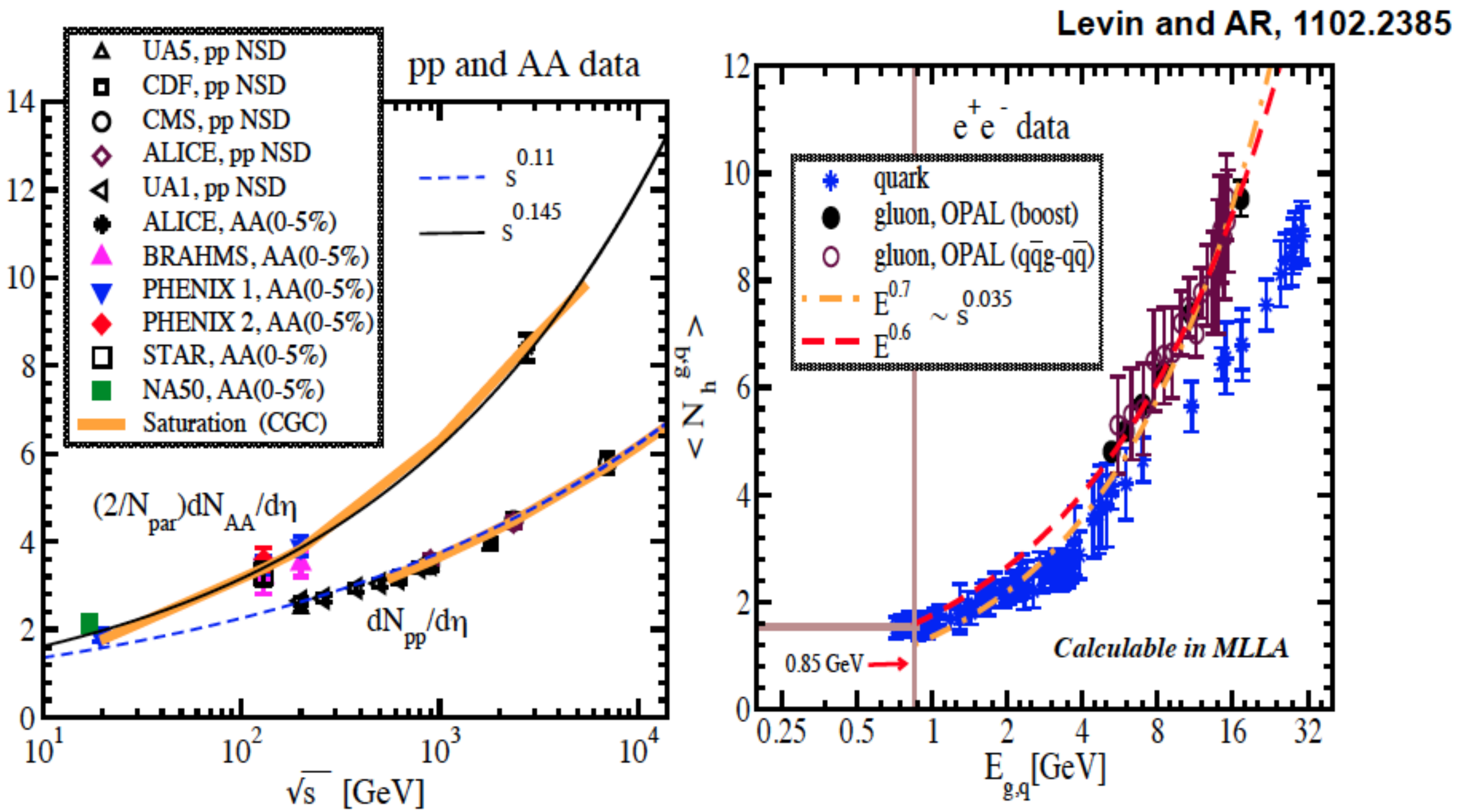




But there exist other non-saturation interpretations. Are there really no or even a negative number of "valence gluons" in the proton for small x?



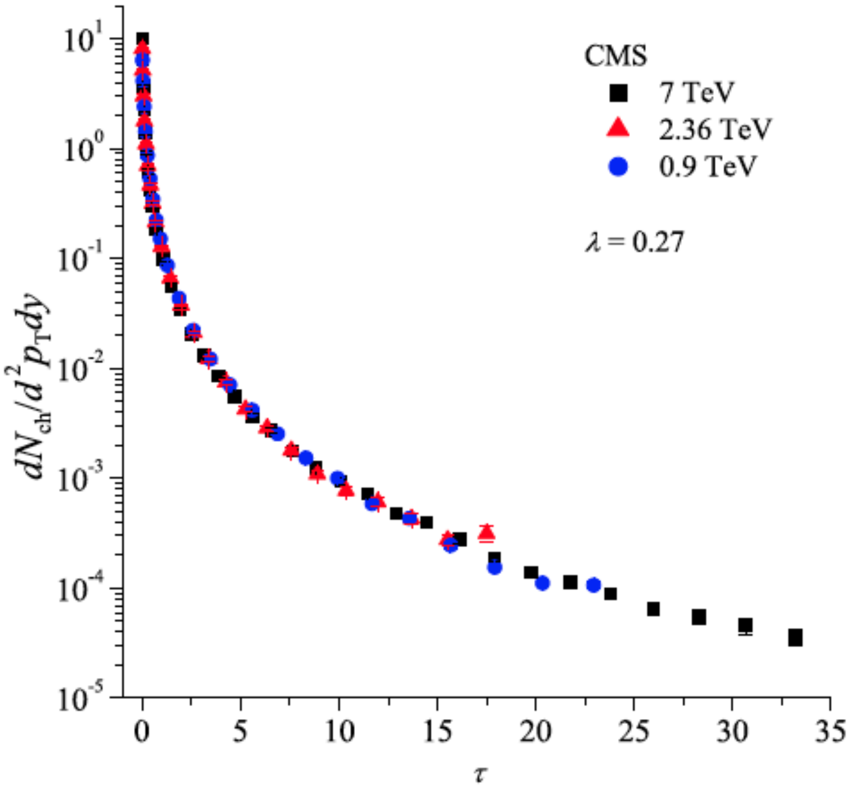
Dependence of Multiplicity on Energy Understood

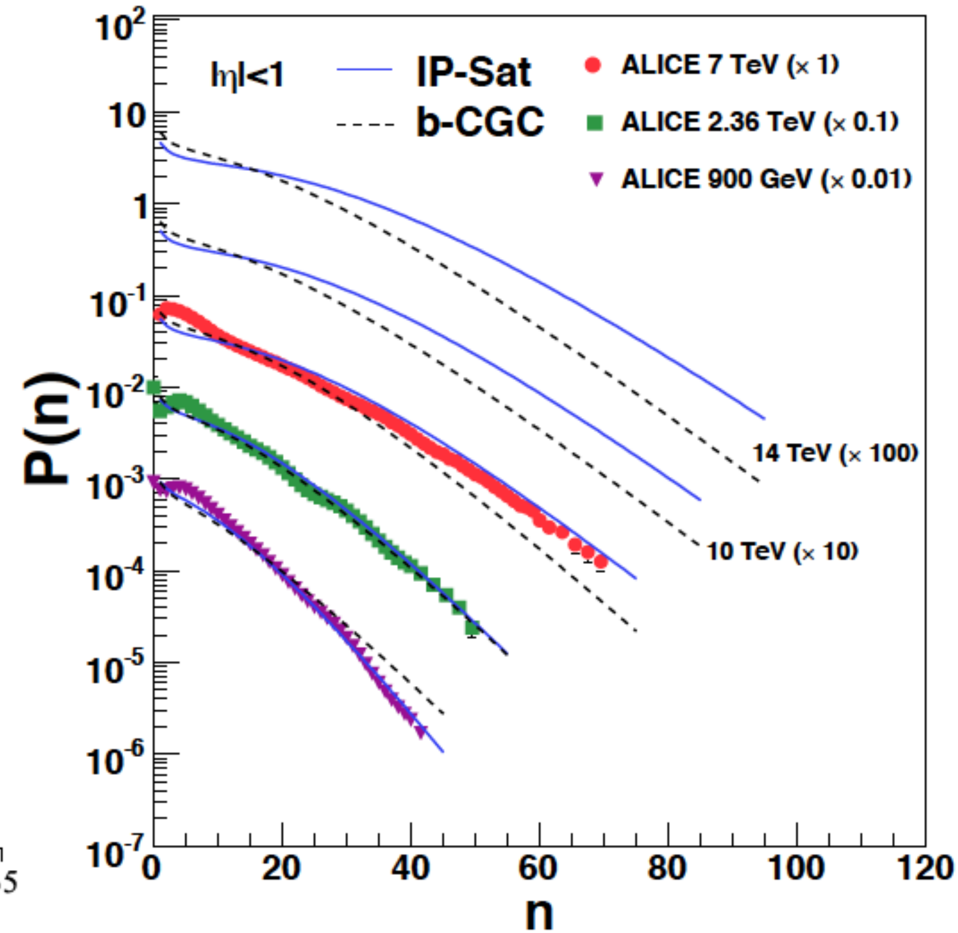


$$\frac{dN_h}{d\eta} \propto Q_s^2 \propto s^{0.11} \quad \text{for} \quad Qs \leq 1 \text{ GeV}$$

$$\frac{dN_h}{d\eta} \propto s^{0.11} * s^{0.035} = s^{0.145} \quad \text{for} \quad Qs > 1 \text{ GeV}$$

Transverse momentum distributions in LHC pp collisions have geometric scaling
Fluctuations in pp collisions follow predictions form CGC-Glasma



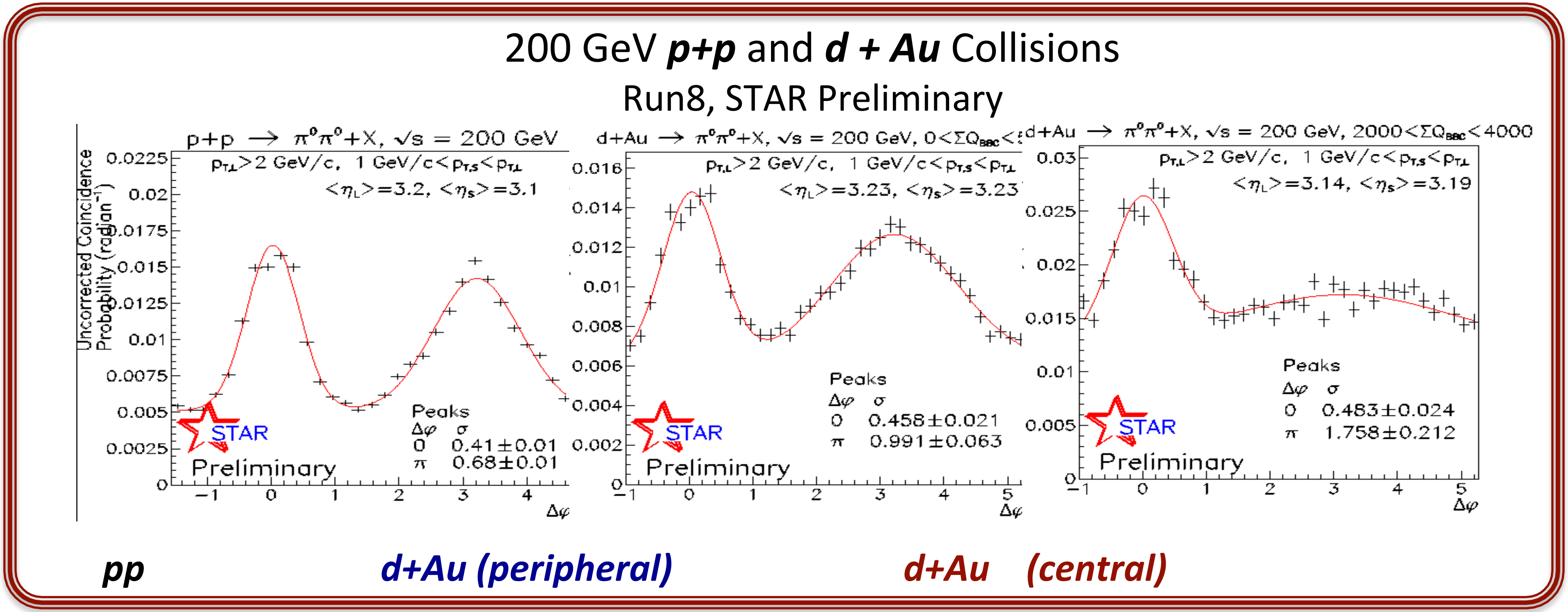


$$\frac{1}{\pi R^2}\frac{dN}{dyd^2p_T} \sim \frac{1}{\alpha_s}F(p_t/Q_{sat}(p_t))$$

Negative binomial and KNO quantitatively predicted by CGC-Glasma

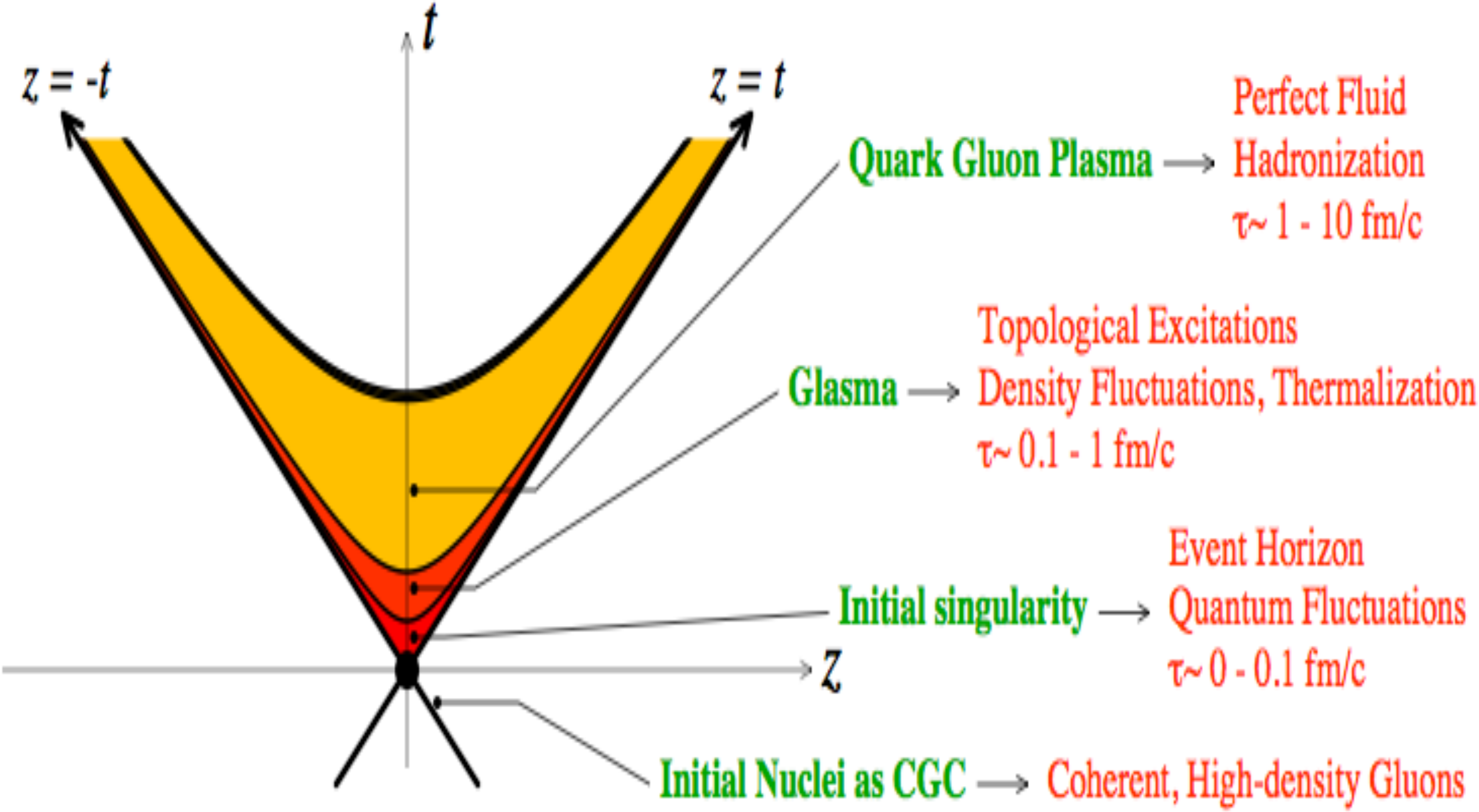
“Jet Quenching” in dA Collisions:

Forward backward angular correlation between forward produced, and forward-central produced particles



No such backward suppression was found in dA at central rapidity

Now very sophisticated understanding and computation for both STAR and PHENIX results (G. Chirilli F. Yuan, B-W Xiao)

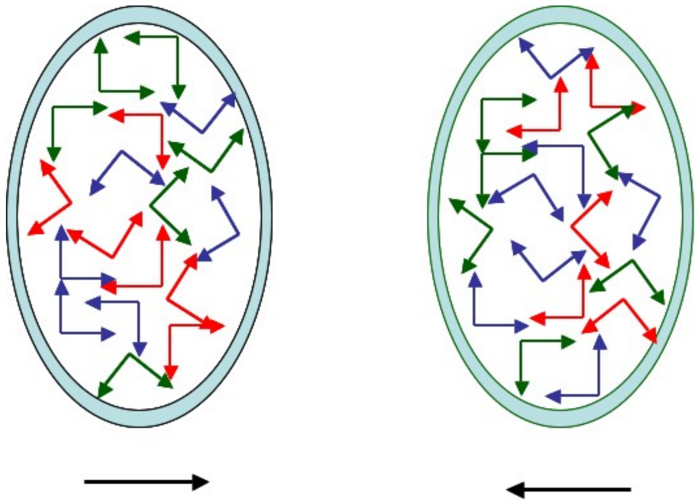


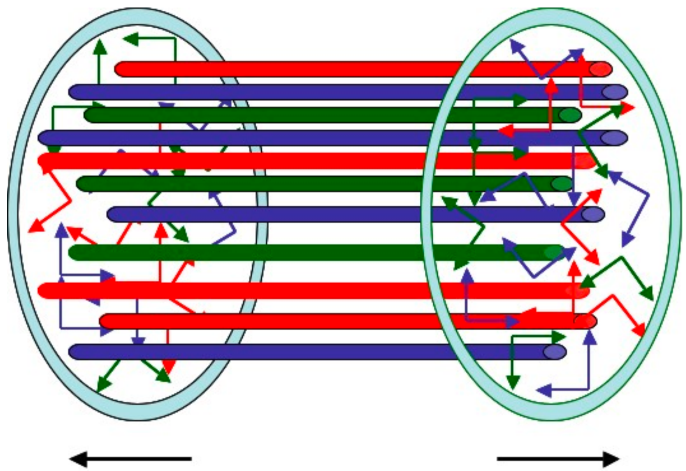
Space Time Picture of Hadron Collisions very similar to that of Big Bang Cosmology

Time scales much smaller

Collisions of two sheets of colored glass

Sheets get dusted with color electric and color magnetic fields





Long range color fields form in very short time

Maximal local density of topological charge: Large local fluctuations in CP violating

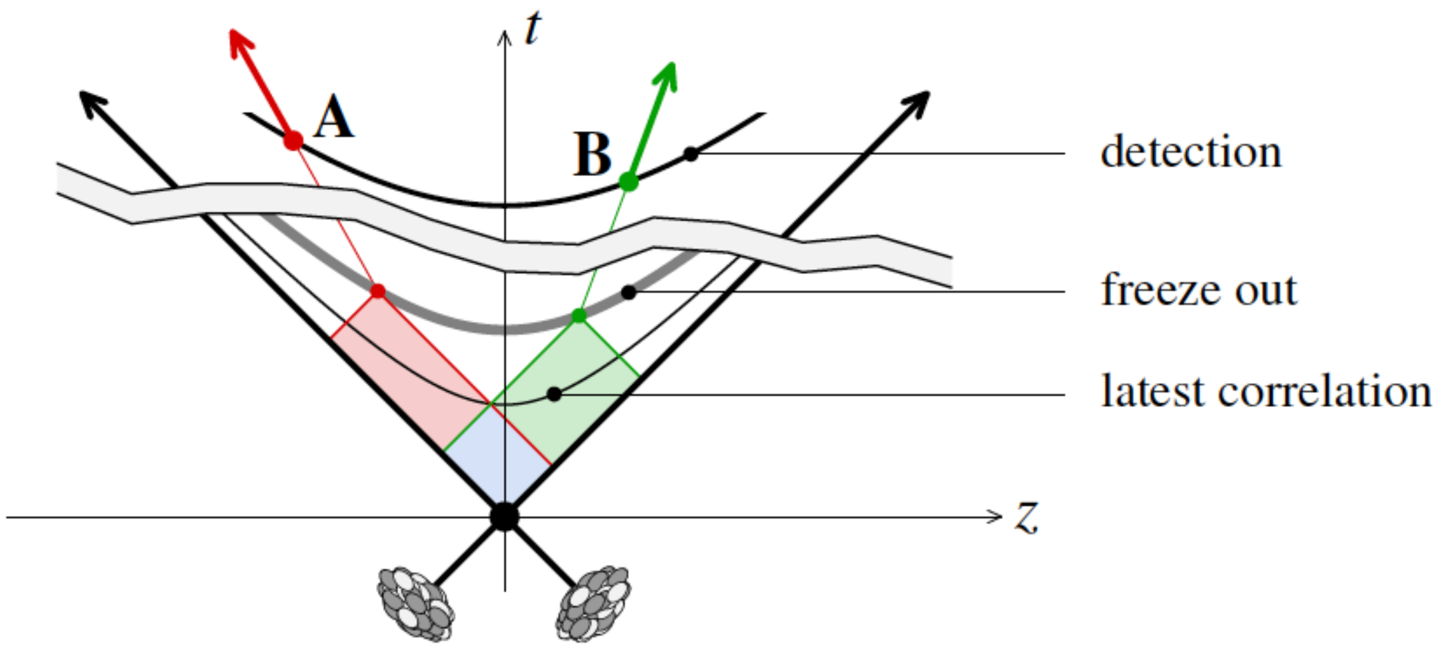
$$\vec{E} \cdot \vec{B}$$

Glasma: Matter making the transition for Color Glass Condensate to Quark Gluon Plasma

The initial conditions for a Glasma evolve classically and the classical fields radiate into gluons
Longitudinal momentum is red shifted to zero by longitudinal expansion

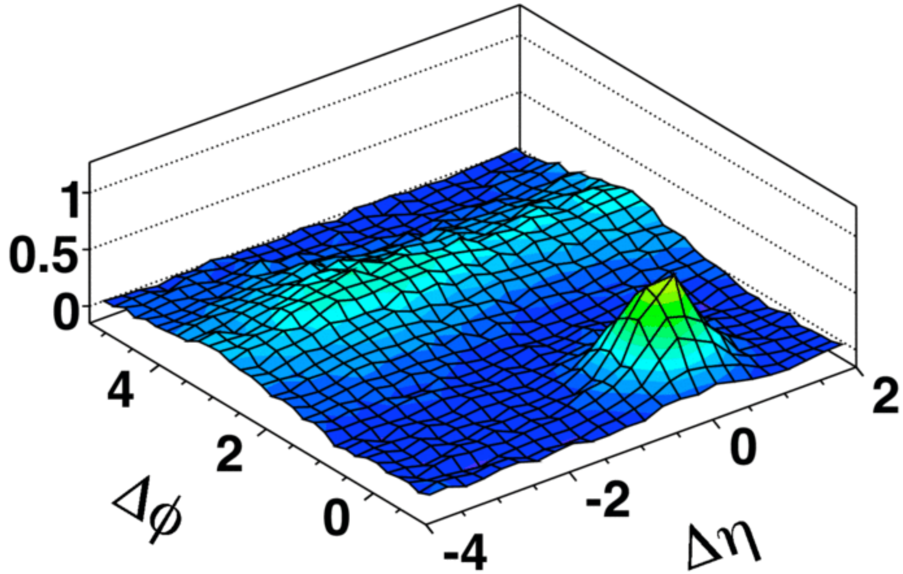
But the classical equations are chaotic:
Small deviations grow exponentially in time

Space–Time picture of Heavy–Ion collisions II



$$\tau \lesssim \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}\,|y_A - y_B|\right)$$

Near-side correlations, ΔΦ<<π (the "ridge")

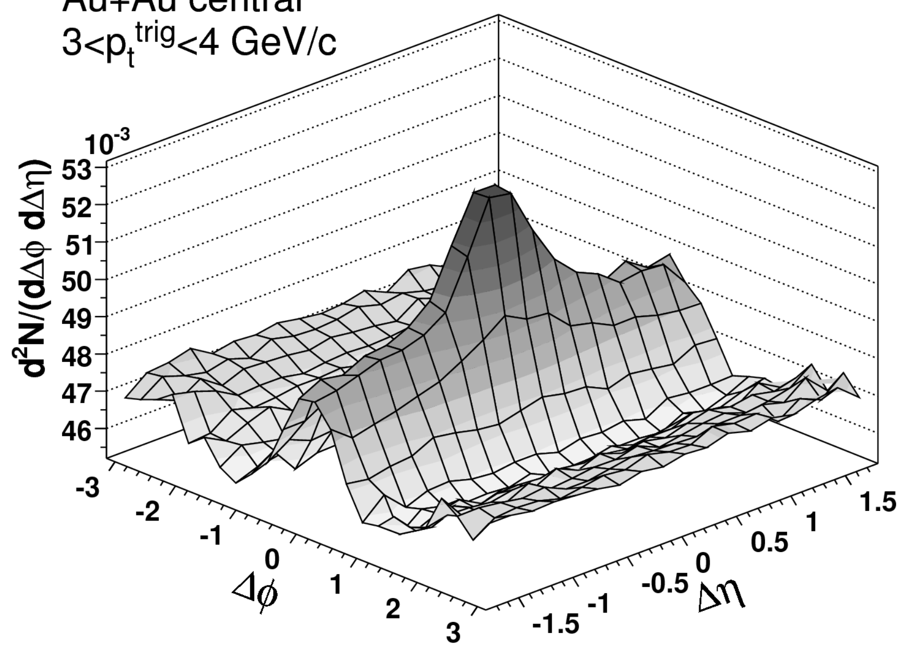


STAR (arXiv:0909.0191)

PYTHIA pp, p_T^{trig} > 2.5 GeV

PHOBOS (arXiv:0903.2811):

$$ln(z\Lambda_{QCD}) \sim \Delta\eta$$

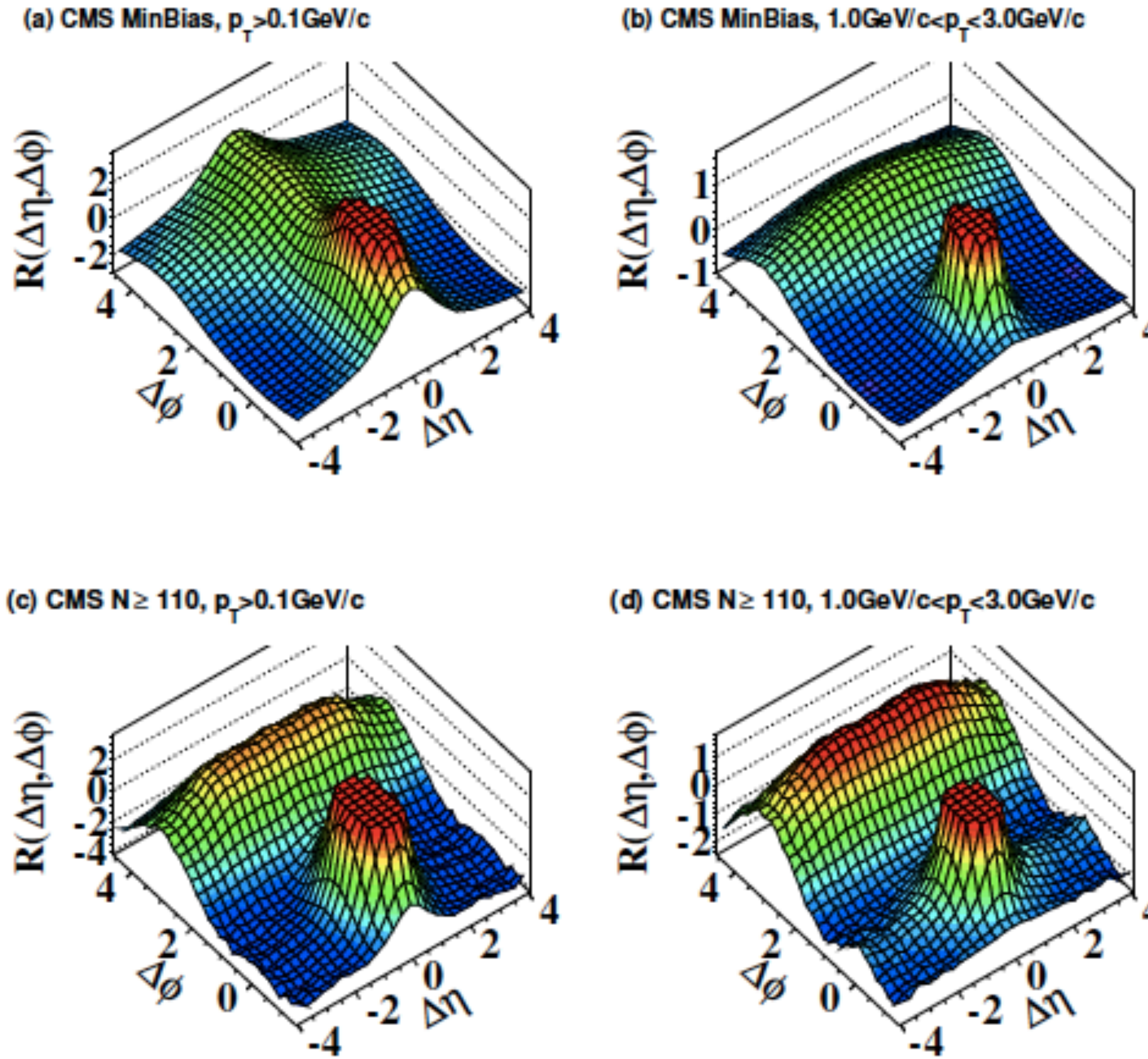


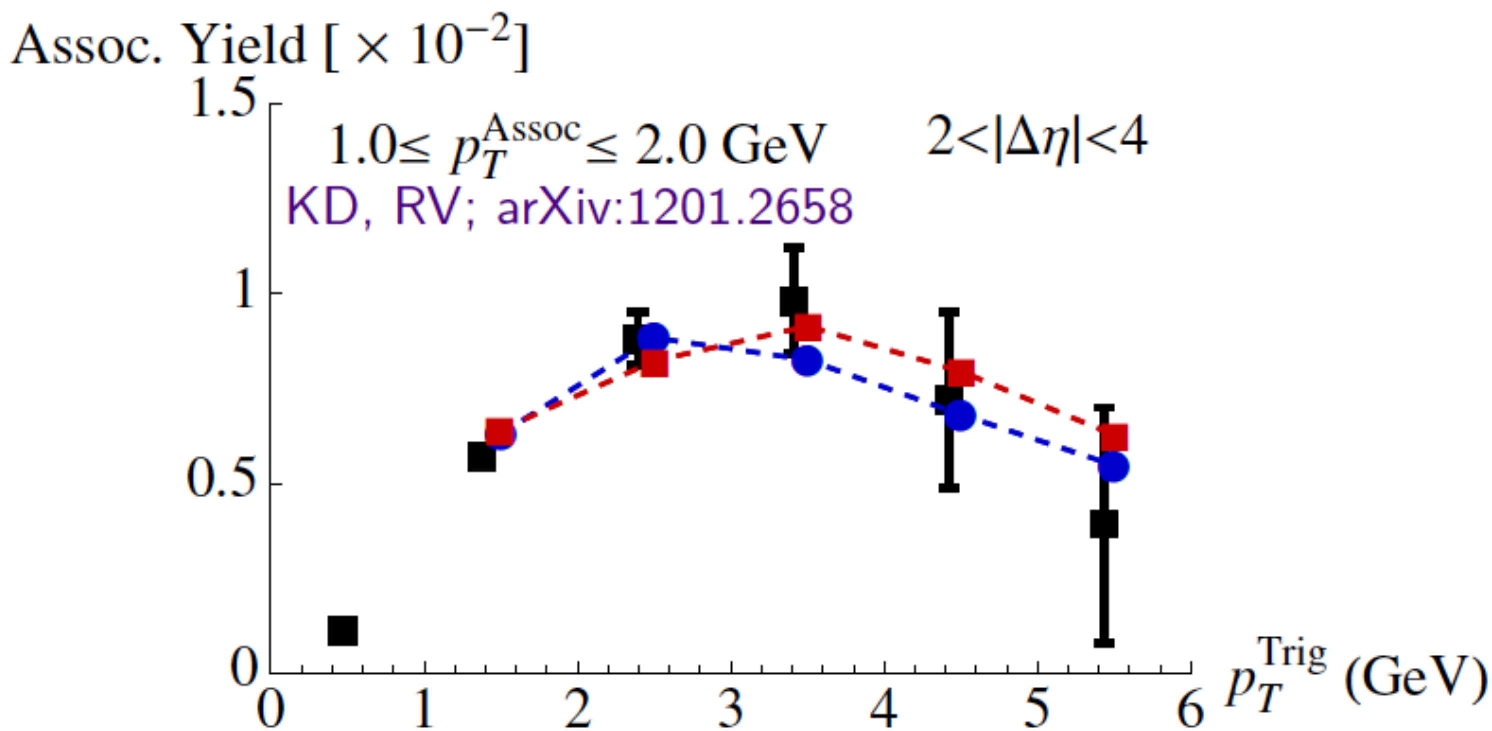
Causality requires that correlations of long range in rapidity must be made very early:

Not originating in QGP

Not jet interactions

CMS Sees Ridge over 8 units of rapidity! High Multiplicity Events
p_T ~ 1-3 Gev





Red: Harder Fragmentation

$D = 2(1-x)/x$

Blue: Softer Fragmentation

$D = 3(1-x)^2/x$

The Ridge is a Snapshot of a Color Electric or Magnetic Flux

LHC:

Tubes exist on sub-fermi transverse size scale
Perhaps as small as .2 Fm
They are formed very early in the collision

Angular peaking:

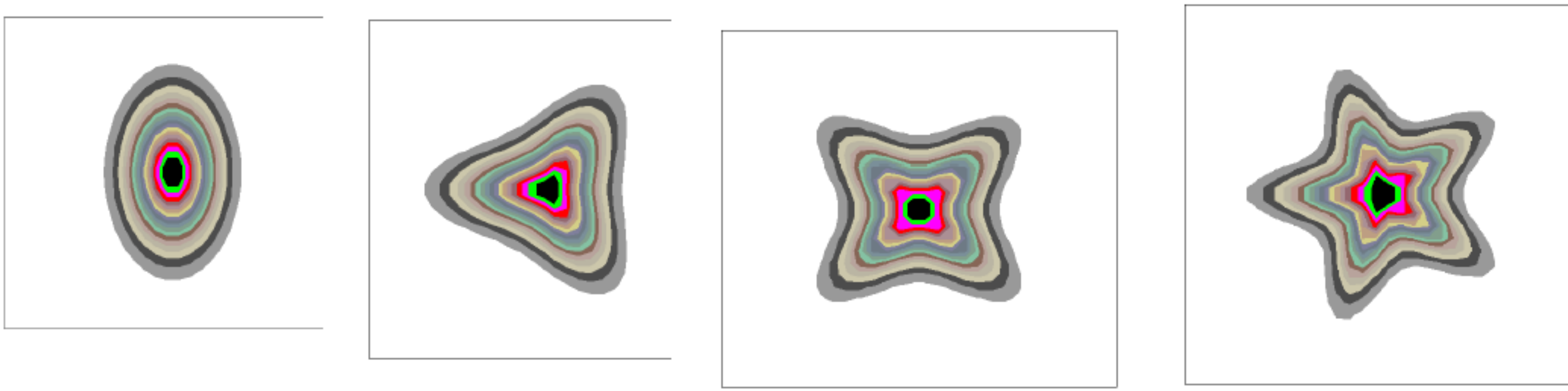
Intrinsic peaking at emission?
Opacity?
Flow or nascent flow effects?

Probably different combination of mechanisms:

High multiplicity pp
High transverse momentum AA
Inclusive AA

Higher order Eccentricities in AA

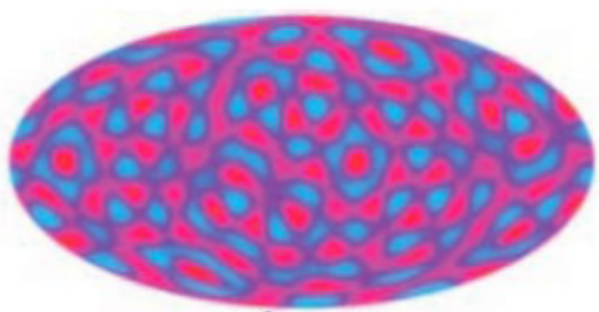
$$\epsilon_n = \frac{\sqrt{\langle r^2 \cos(n\phi)\rangle^2 + \langle r^2 \sin(n\phi)\rangle^2}}{\langle r^2 \rangle}$$



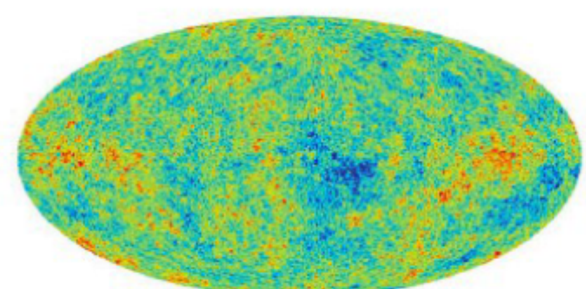
Analogy: CMB

A. Mocsy & P. Sorensen

$\ell = 2$



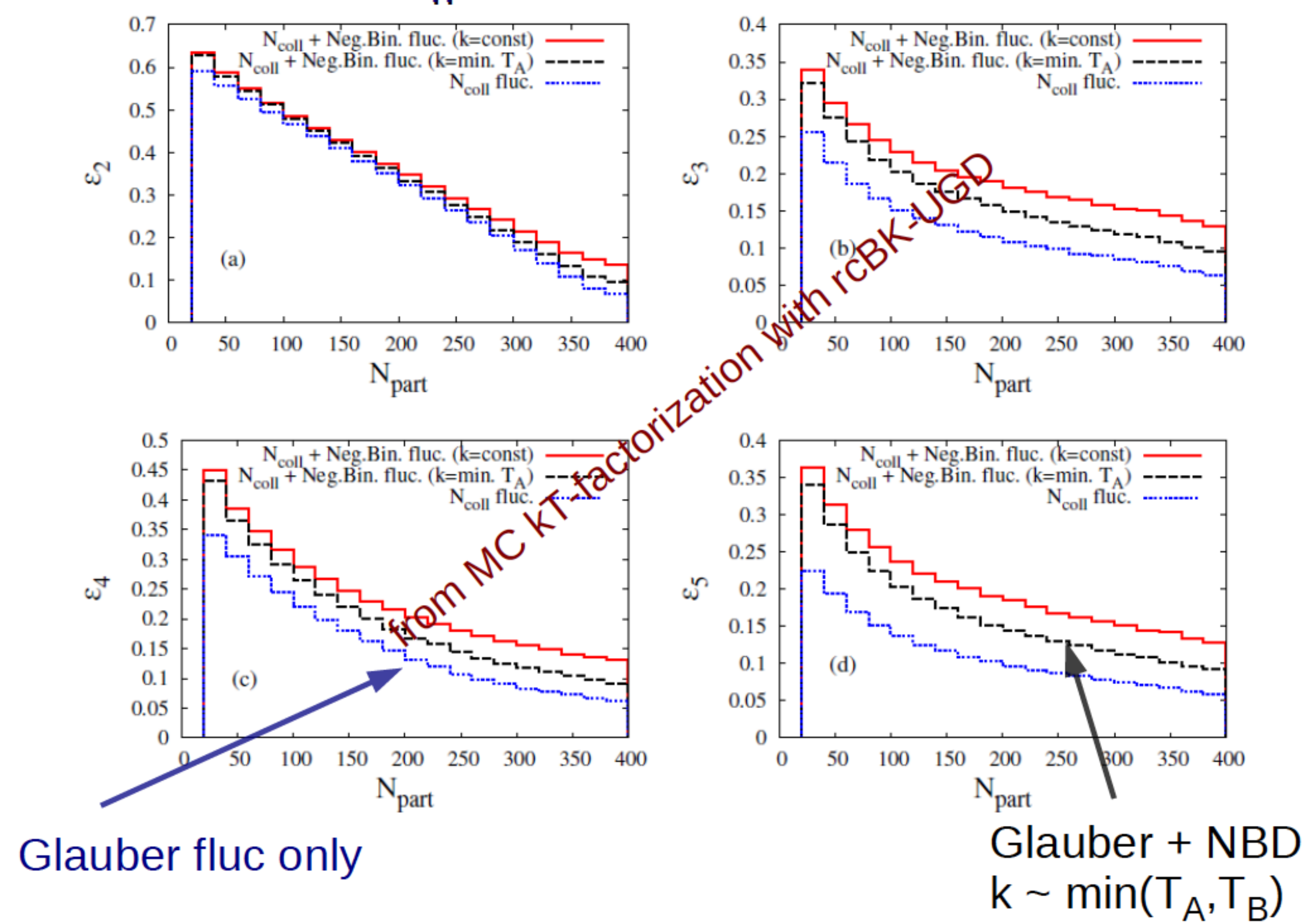
$\ell = 16$



sum l

Sources of Initial Fluctuations in the Transverse Plane:
(always need longitudinal correlations generated by tubular flux tube structures)

Eccentricities ε_n in Au+Au



Fluctuations of positions of nucleons in the collisions

Fluctuations in the multiplicity of decays of flux tubes (a boost invariant negative binomial distribution)

Thermalization of the Glasma

Chaos and Turbulence:

CGC field is rapidity independent => occupies restricted range of phase space
Wiggling strings have much bigger classical phase space
A small perturbation that has longitudinal noise grows exponentially

$$A_{classical} \sim 1/g$$

$$A_{quantum} \sim 1$$

After a time

$$t \sim \frac{ln^p(1/g)}{Q_{sat}}$$

system isotropizes,

But it has not thermalized!

Thermalization naively occurs when scattering times are small compared to expansion times. Scattering is characterized by a small interaction strength.

How can the system possibly thermalize, or even strongly interact with itself?

Initial distribution:

$$\frac{dN}{d^3x d^3p} \sim \frac{Q_{sat}}{\alpha_s E} \; F(E/Q_{sat})$$

A thermal distribution would be:

$$\frac{dN}{d^3x d^3p} \sim \frac{1}{e^{E/T} - 1} \sim T/E$$

Only the low momentum parts of the Bose-Einstein distribution remain

$$E \sim Q_{sat}$$

$$\text{“}T \sim Q_{sat}/\alpha_s\text{”}$$

As dynamics migrates to UV, how do we maintain isotropy driven by infrared modes with a scale of the saturation momentum?

Phase space is initially over-occupied

$$f_{thermal} = \frac{1}{e^{(E-\mu)/T} - 1}$$

Chemical potential is at maximum the particle mass

$$\rho_{max} \sim T^3 \qquad \epsilon_{max} \sim T^4$$

$$\rho_{max}/\epsilon_{max}^{3/4} \leq C$$

But for isotropic Glasma distribution

$$\rho_{max}/\epsilon_{max}^{3/4} \leq 1/\alpha_S^{1/4}$$

Where do the particle gluons go?

If inelastic collisions were unimportant, then as the system thermalized, the ratio of the energy density and number density are conserved

$$f_{thermal} = \rho_{cond}\delta^3(p) + \frac{1}{e^{(E-m)/T} - 1}$$

One would form a Bose-Einstein Condensate

Over-occupied phase space => Field coherence in important
Interactions can be much stronger than

$$g^2$$

$$N_{coh}g^2$$

Might this be at the heart of the large amount of jet quenching, and strong flow patterns seen at RHIC?

Problem we tried to solve:

Blaizot, Gelis, Jin-Feng Liao, LM, R. Venugopalan

How does the system evolve from an early time over-occupied distribution to a thermalized distribution

We argue that the system stays strongly interacting with itself during this time due to coherence

First: Kinetic Evolution Dominated by Elastic Collisions in a Non-Expanding Glasma

$$\partial_t f(p,X) = C_p[f]$$

$$f(p,X) = \frac{\Lambda_s(t)}{\alpha_s p} g(p/\Lambda(t))$$

$$\Lambda_s(t_i) \sim \Lambda(t_i) \sim Q_{sat}$$

Small angle approximation for transport equation:

Blaizot, Liao, LM

$$\left.\frac{\partial f}{\partial t}\right|_{\mathrm{coll}} \sim \frac{\Lambda_s^2 \Lambda}{p^2} \partial_p \left\{ p^2 \left[\frac{df}{dp} + \frac{\alpha_s}{\Lambda_s} f(p)(1+f(p)) \right] \right\}$$

$$\frac{\Lambda \Lambda_s}{\alpha_s} \equiv - \int_0^\infty dp\, p^2 \frac{df}{dp}$$

$$\frac{\Lambda \Lambda_s^2}{\alpha_s^2} \equiv \int_0^\infty dp\, p^2 f(1+f)$$

Due to coherence, the collision equation is independent of coupling strength!

There is a fixed point of this equation corresponding to thermal equilibrium when

$$T \sim \Lambda \sim \Lambda_s/\alpha_s$$

Estimates of various quantities
(Momentum integrations are all dominated by the hard scale)

$$n_g \sim \frac{1}{\alpha_s}\Lambda^2\Lambda_s \qquad \epsilon_g \sim \frac{1}{\alpha_s}\Lambda_s\Lambda^3 \qquad \frac{\epsilon_g}{n_g} \sim \Lambda$$

$$n = n_c + n_g \qquad \epsilon_c \sim n_c m \sim n_c\sqrt{\Lambda\Lambda_s}$$

$$m^2 \sim \alpha_s \int dp\, p^2 \frac{df(p)}{d\omega_p} \sim \Lambda\Lambda_s$$

The collision time follows from the structure of the transport equation and is

$$t_{scat} = \frac{\Lambda}{\Lambda_s^2}$$

The scattering time is independent of the interaction strength

Thermalization in a non-expanding box

$$\epsilon = \Lambda_s \Lambda^3 \sim constant \qquad\qquad t_{scat} = \frac{\Lambda}{\Lambda_s^2} \sim t$$

So that

$$\Lambda_s \sim Q_s \left(\frac{t_0}{t}\right)^{\frac{3}{7}} \qquad\qquad \Lambda \sim Q_s \left(\frac{t}{t_0}\right)^{\frac{1}{7}}$$

$$n_g \sim n_0 \left(\frac{t_o}{t}\right)^{1/7} \qquad m \sim Q_s (t_0/t)^{1/7} \qquad \frac{\epsilon_c}{\epsilon_g} \sim \left(\frac{t_0}{t}\right)^{1/7}$$

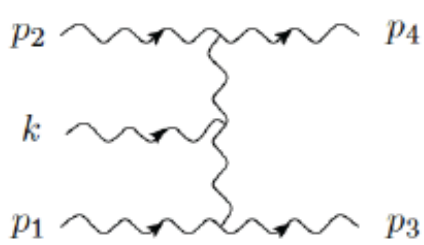
$$s \sim \Lambda^3 \sim Q_s^3 (t/t_0)^{3/7}$$

At thermalization $\Lambda_s = \alpha_s \Lambda$

$$t_{th} \sim \frac{1}{Q_s}\left(\frac{1}{\alpha_s}\right)^{\frac{7}{4}} \qquad\qquad s \sim Q_s^3/\alpha_s^{3/4} \sim T^3$$

How do inelastic processes change this?

Rates of inelastic and elastic processes are parametrically the same



$$\frac{1}{t_{scat}} \sim \alpha_s^{n+m-2} \left(\frac{\Lambda_s}{\alpha_s}\right)^{n+m-2} \left(\frac{1}{m^2}\right)^{n+m-4} \Lambda^{n+m-5}$$

$$m^2 \sim \Lambda_s \Lambda$$

$$t_{\mathrm{scat}} = \frac{\Lambda}{\Lambda_{\mathrm{s}}^2},$$

What about the condensate? Difficult to make definite statement.
In relaxation time limit, we would expect:

$$\frac{d}{dt}\rho_{cond} = -\frac{a}{t_{scat}}\rho_{cond} + \frac{b}{t_{scat}} n_{gluons}$$

Either $\rho_{cond} >> n_{gl}$ or $\rho_{cond} = \frac{b}{a} n_{gluons}$

Condensate would rapidly evaporate near thermalization time

Effect of Longitudinal Expansion

$$\partial_t f - \frac{p_z}{t}\partial_{p_z} f = \left.\frac{df}{dt}\right|_{p_z t} = C[f] \qquad \partial_t \epsilon + \frac{\epsilon + P_L}{t} = 0$$

Assume approximate isotropy restored by scattering.
Will check later that this is consistent.

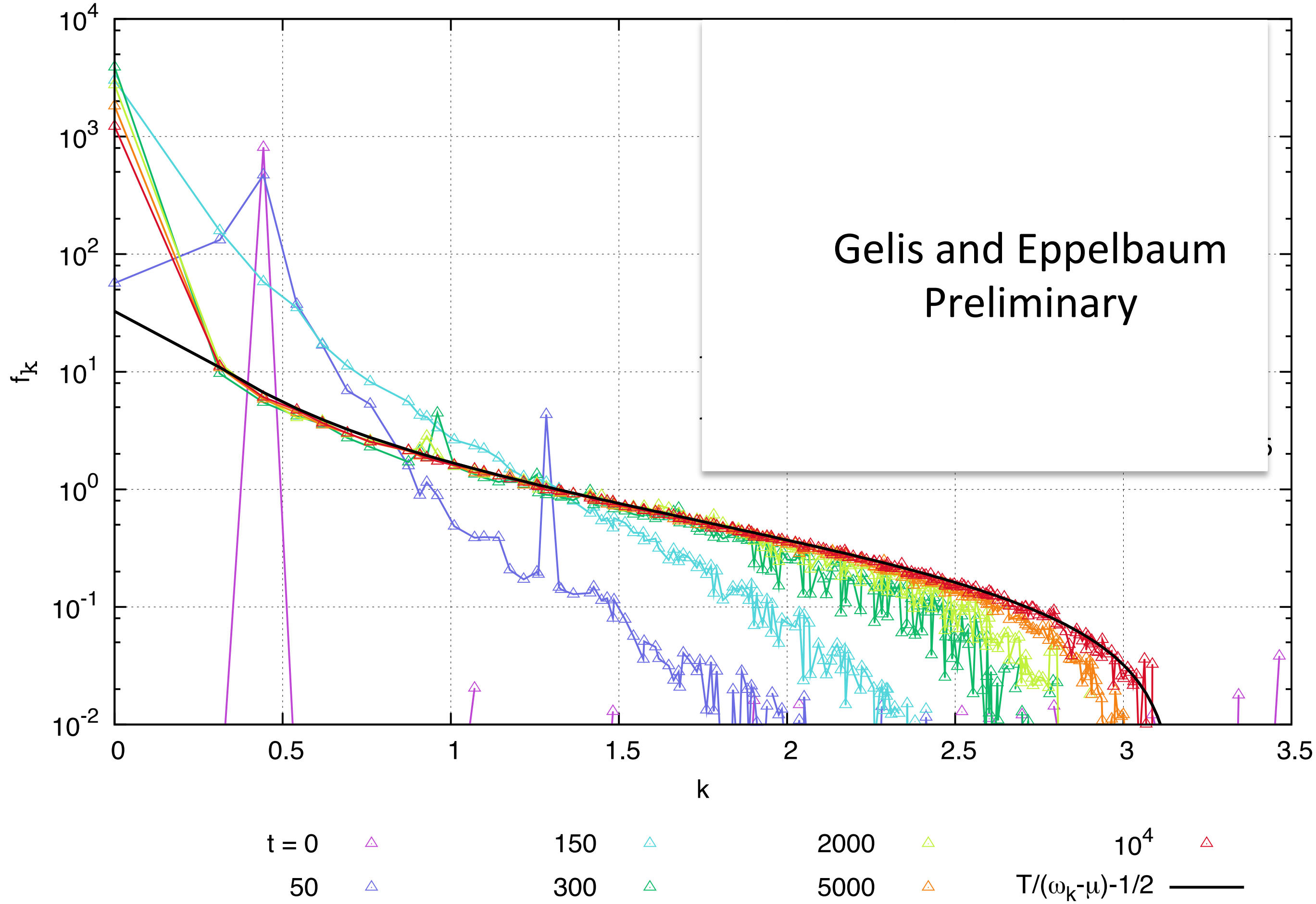
$$P_L = \delta\epsilon \qquad 0 < \delta < 1/3$$

$$\epsilon_g(t) \sim \epsilon(t_0)\left(\frac{t_0}{t}\right)^{1+\delta} \qquad \Lambda_s \sim Q_s\left(\frac{t_0}{t}\right)^{(4+\delta)/7}, \qquad \Lambda \sim Q_s\left(\frac{t_0}{t}\right)^{(1+2\delta)/7}$$

$$\left(\frac{t_{\rm th}}{t_0}\right) \sim \left(\frac{1}{\alpha_s}\right)^{\frac{7}{3-\delta}}$$

$$< p_x^2 > / < p_T^2 > \sim constant$$

Simulations by Gelis and Eppelbaum seem to confirm this scenario in scalar field theory



Rapid Reaction Task Force at Heidelberg sponsored by EMMI Dec 12-14